

SEARCH AND IDENTIFICATION OF EXTRA SPATIAL DIMENSIONS AT LHC¹

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Abstract

We present an analysis, based on the center–edge asymmetry, to distinguish effects of extra dimensions within the Arkani-Hamed–Dimopoulos–Dvali (ADD) and Randall–Sundrum (RS) scenarios from other new physics effects in lepton-pair production at the CERN Large Hadron Collider LHC. Spin-2 and spin-1 exchange can be distinguished up to an ADD cut-off scale, M_H , of about 5 TeV, at the 95% CL. In the RS scenario, spin-2 resonances can be identified in most of the favored parameter space.

1 Introduction

A general feature of the different theories extending the Standard Model of elementary particles (SM) is that new interactions involving heavy elementary objects and mass scales should exist, and manifest themselves *via* deviations of measured observables from the SM predictions. While for the supersymmetric extensions of the SM, there is confidence that the new particles could be directly produced and their properties studied, in numerous other cases, such as the composite models of fermions[1] and the exchange of leptoquarks,[2] existing limits indicate that the heavy states could not be produced even at the highest energy supercolliders and, correspondingly, only “virtual” effects can be expected. A description of the relevant new interaction in terms of “effective” contact-interaction (CI) is most appropriate in these cases. Of course, since different interactions can give rise to similar deviations from the SM predictions, the problem is to identify, from a hypothetically measured deviation, the kind of new dynamics underlying it.

In the context of the hierarchy problem, much attention has been given in the past few years to the different scenarios involving extra space dimensions and their manifestations at high energy electron-positron and proton-(anti)proton colliders. Of particular relevance is the problem of differentiating their signals from other sources of new phenomena. We shall here discuss the possibility

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of distinguishing such effects of extra dimensions from other NP scenarios in lepton pair production at the LHC:

$$p + p \rightarrow l^+ l^- + X, \quad (1)$$

where $l = e, \mu$. Two specific models involving extra dimensions will be considered, namely the ADD[3] and RS[4] scenarios.

In the ADD scenario,[3] gravity is allowed to propagate in two or more compactified extra space dimensions, with up to millimeter size R . In four dimensions, this mechanism is equivalent to the exchange of a tower of equally mass-separated Kaluza-Klein (KK) spin-2 states, with $\Delta M \sim 1/R$. The relation between the higher-dimensional Planck scale M_D and the four-dimensional Planck scale M_{Pl} is:

$$M_{\text{Pl}}^2 \sim R^n \times M_D^{n+2}, \quad (2)$$

where n is the number of extra dimensions. The sum over the (almost continuous) spectrum of KK states (of mass $m_{\vec{n}}$) can be expressed as :[5]

$$\sum_{\vec{n}=1}^{\infty} \frac{G_N}{M^2 - m_{\vec{n}}^2} \rightarrow \frac{-\lambda}{\pi M_H^4}, \quad (3)$$

where λ is a sign factor, G_N is Newton's constant, and M_H is the cutoff scale, expected to be of the order of the TeV scale. Equation (3) can be considered as an effective interaction at the scale M_H .

We will limit ourselves to the simplest version of the RS scenario,[4] with only one extra dimension. Differently from the ADD scenario, there will be narrow graviton spin-2 resonances with masses of the order of TeV and coupling strength comparable to weak interactions. Furthermore, the spectrum of KK gravitons in the tower are unequally spaced, as being located at the Bessel zeros x_n :

$$m_n = x_n \Lambda_\pi \frac{k}{M_{\text{Pl}}} = m_1 \frac{x_n}{x_1} \quad (4)$$

where Λ_π is the KK coupling strength.

This model has two independent parameters, conveniently taken to be k/\bar{M}_{Pl} and m_1 , where k is a constant of $\mathcal{O}(\bar{M}_{\text{Pl}})$, and m_1 is the mass of the first graviton resonance. Also, the phenomenology is quite different from that of the ADD scenario, in the sense that RS resonances may well be in the energy range of the LHC, and hence show up as peaks in the cross section.

2 Center-edge asymmetry A_{CE}

In the SM, lepton pairs can at hadron colliders be produced at tree-level via the following parton-level process

$$q\bar{q} \rightarrow \gamma, Z \rightarrow l^+ l^-. \quad (5)$$

Now, if gravity can propagate in extra dimensions, the possibility of KK graviton exchange opens up two tree-level channels in addition to the SM channels, namely

$$q\bar{q} \rightarrow G \rightarrow l^+ l^-, \quad \text{and} \quad gg \rightarrow G \rightarrow l^+ l^-, \quad (6)$$

where G represents the gravitons of the KK tower.

The center-edge and total cross sections can at the parton level be defined like for initial-state electrons and positrons:[6]

$$\hat{\sigma}_{\text{CE}} \equiv \left[\int_{-z^*}^{z^*} - \left(\int_{-1}^{-z^*} + \int_{z^*}^1 \right) \right] \frac{d\hat{\sigma}}{dz} dz, \quad \hat{\sigma} \equiv \int_{-1}^1 \frac{d\hat{\sigma}}{dz} dz, \quad (7)$$

where $z = \cos \theta_{\text{cm}}$, with θ_{cm} the angle, in the c.m. frame of the two leptons, between the lepton and the proton. Here, $0 < z^* < 1$ is a parameter which defines the border between the “center” and the “edge” regions. This asymmetry has been demonstrated very selective to the ADD effects in the electron-positron case,[6] and we want to test its use in the more complicated (but experimentally forthcoming) subprocesses (5) and (6).

The center-edge asymmetry can then for a given dilepton invariant mass M be defined as

$$A_{\text{CE}}(M) = \frac{d\sigma_{\text{CE}}/dM}{d\sigma/dM}, \quad (8)$$

where a convolution over parton momenta is performed, and we obtain $d\sigma_{\text{CE}}/dM$ and $d\sigma/dM$ from the inclusive differential cross sections $d\sigma_{\text{CE}}/dM dy dz$ and $d\sigma/dM dy dz$, respectively, by integrating over z according to Eq. (7) and over rapidity y between $-Y$ and Y , with $Y = \log(\sqrt{s}/M)$. [7]

For the SM contribution to the center-edge asymmetry, the convolution integrals, depending on the parton distribution functions, cancel, and one finds[7]

$$A_{\text{CE}}^{\text{SM}} = \frac{1}{2} z^* (z^{*2} + 3) - 1. \quad (9)$$

This result is thus independent of the dilepton mass M , and identical to the result for e^+e^- colliders.[6] Hence, in the case of no cuts on the angular integration, there is a unique value, $z^* = z_0^* \simeq 0.596$, for which $A_{\text{CE}}^{\text{SM}}$ vanishes, corresponding to $\theta_{\text{cm}} = 53.4^\circ$.

The SM center-edge asymmetry of Eq. (9) is equally valid for a wide variety of NP models: composite-like contact interactions, Z' models, TeV-scale gauge bosons, *etc.* However, if graviton exchange is possible, the graviton tensor couplings would yield a different angular distribution, leading to a different dependence of A_{CE} on z^* . In this case, the center-edge asymmetry would not vanish for the above choice of $z^* = z_0^*$. Furthermore, it would show a non-trivial dependence on M . Thus, a value for A_{CE} different from $A_{\text{CE}}^{\text{SM}}$ would indicate non-vector-exchange NP.

Another important difference from the SM case is that the graviton also couples to gluons, and therefore it has the additional gg initial state of Eq. (6) available. In summary then, including graviton exchange and also experimental cuts relevant to the LHC detectors, the center-edge asymmetry is no longer the simple function of z^* given by Eq. (9). [7]

3 Identifying graviton exchange and graviton resonance

We assume now that a deviation from the SM is discovered in the cross section, either in the form of a CI or a resonance. We will here investigate in which

regions of the ADD and RS parameter spaces such a deviation can be *identified* as being caused by spin-2 exchange. More precisely, we will see how the center-edge asymmetry (8) can be used to exclude spin-1 exchange interactions beyond that of the SM. At the LHC, with luminosity $\mathcal{L}_{\text{int}} = 100$ and 300 fb^{-1} , we require the invariant lepton mass $M > 400 \text{ GeV}$ and divide the data into 200 GeV bins as long as the number of events in each bin, $\epsilon_l \mathcal{L}_{\text{int}} \sigma(i)$, is larger than 10. Here, ϵ_l is the experimental reconstruction efficiency and $\sigma(i)$ the cross section in bin i . To compute cross sections we use the CTEQ6 parton distributions.[8] We impose angular cuts relevant to the LHC detectors. The lepton pseudorapidity cut is $|\eta| < \eta_{\text{cut}} = 2.5$ for both leptons, and in addition to the angular cuts, we impose on each lepton a transverse momentum cut $p_{\perp} > p_{\perp}^{\text{cut}} = 20 \text{ GeV}$.

From a conventional χ^2 analysis we find the ADD-scenario *identification* reach on M_H at the LHC summarized in Table 1. In this table we also include the identification reach obtained from the analysis of the center-edge asymmetry performed at an e^+e^- Linear Collider (LC) for c.m. energy 500 GeV.

Table 1: Identification reach on M_H at 95% CL from A_{CE} .

Collider	LHC 100 fb^{-1}	LHC 300 fb^{-1}	LC 50 fb^{-1}	LC 500 fb^{-1}
$\lambda = +1 \text{ (TeV)}$	4.8	5.4	3.1	4.1
$\lambda = -1 \text{ (TeV)}$	5.0	5.9	3.1	4.1

As displayed in Eq. (4), in the RS scenario the resonances are unevenly spaced. If the first resonance is sufficiently heavy, the second resonance would be difficult to resolve within the kinematical range allowed experimentally at the LHC, and we shall now consider this situation.

We choose a 200 GeV bin around the RS resonance mass m_1 , and obtain the results presented in Fig. 1, where we display the 2, 3 and 5σ contours for $\mathcal{L}_{\text{int}} = 100$ and 300 fb^{-1} . As shown in this figure, the identification reach at the LHC provided by the observable A_{CE} covers a large portion of the “theoretically preferred” (in order not to create additional hierarchies) parameter space $\Lambda_{\pi} < \mathcal{O}(10) \text{ TeV}$. For $k/\bar{M}_{\text{Pl}} = 0.1$, the $\mathcal{L}_{\text{int}} = 100 \text{ fb}^{-1}$ identification reach extends above $m_1 \simeq 3.5 \text{ TeV}$ (at the 2σ level).

In conclusion, we have considered the ADD scenario parametrized by M_H , and the RS scenario parametrized by m_1 and k/\bar{M}_{Pl} . Although somewhat higher sensitivity reaches on M_H or m_1 than obtained here are given by other approaches, this method based on A_{CE} is suitable for actually *pinning down* the spin-2 nature of the KK gravitons up to very high M_H or m_1 . This is different from just detecting deviations from the Standard Model predictions, and is a way to obtain additional information on the underlying new-physics scenario and to impose stringent constraints on the extra dimension scenarios here discussed. Therefore, the analysis sketched here can potentially represent a valuable method complementary to the direct fit to the angular distribution of the lepton pairs.[9, 10] Also, the analysis can readily be extended to other final states, in high energy proton-proton collisions, different from l^+l^- in (1), such as di-photon or di-jet final states.

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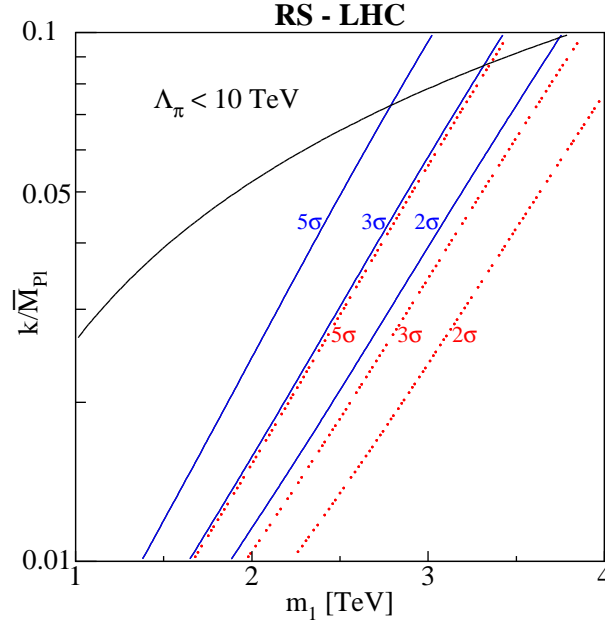


Figure 1: Spin-2 identification of an RS resonance, using the center–edge asymmetry, integrated over bins of 200 GeV around the peak. Solid (dotted) 2σ , 3σ , 5σ contours: $\mathcal{L}_{\text{int}} = 100 \text{ fb}^{-1}$ (300 fb^{-1}). The theoretically favored region, $\Lambda_\pi < 10 \text{ TeV}$, is indicated.

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